

# Interaction correction to the conductivity of two-dimensional electron gas in $\text{In}_x\text{Ga}_{1-x}\text{As}/\text{InP}$ quantum well structure with strong spin-orbit coupling

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The electron-electron interaction quantum correction to the conductivity of the gated single quantum well  $\text{InP}/\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$  heterostructures is investigated experimentally. The analysis of the temperature and magnetic field dependences of the conductivity tensor allows us to obtain reliably the diffusion part of the interaction correction for different values of spin relaxation rate,  $1/\tau_s$ . The surprising result is that the spin relaxation processes do not suppress the interaction correction in the triplet channel and, thus, do not enhance the correction in magnitude contrary to theoretical expectations even in the case of relatively fast spin relaxation,  $1/T\tau_s \simeq (20 - 25) \gg 1$ .

## I. INTRODUCTION

A weak localization (WL) quantum correction to the conductivity,  $\delta\sigma^{WL}$ , and the correction due to electron-electron ( $e$ - $e$ ) interaction,  $\delta\sigma^{ee}$ , are responsible for the temperature and magnetic field dependences of the conductivity and Hall effect in the two-dimensional electron gas at low temperatures, when the Fermi energy ( $E_F$ ) is much greater than the temperature ( $T$ ) and the phonon scattering is negligible. Magnitude of these corrections is strongly dependent on the spin-relaxation rate  $1/\tau_s$ , which is determined by strength of spin-orbit interaction (SOI). When the spin relaxation is slow,  $\tau_s \gg \tau_\phi$ , as it takes place in the systems with the weak spin-orbit coupling, the WL correction is negative and for the case of the one valley energy spectrum is  $\delta\sigma^{WL} = -G_0 \ln(\tau_\phi/\tau)$ , where  $\tau_\phi$  and  $\tau$  are the phase relaxation and transport times, respectively,  $G_0 = e^2/\pi h$ . Applying a transverse magnetic field destroys the interference resulting in negative magnetoresistance. Namely analysis of the shape of the negative magnetoresistance is a powerful tool allowing us to extract experimentally the phase relaxation time in different systems.<sup>1-3</sup> The increase of SOI strength leads to shortage of the spin relaxation time and to appearance of the positive magnetoresistivity against the negative magnetoresistivity background when  $\tau_s \lesssim \tau_\phi$ . This effect known as the weak antilocalization has been first reported for 2D structures about two decades ago<sup>4,5</sup> and widely used to date to obtain the spin relaxation time experimentally.<sup>6,7</sup> In the limiting case of  $\tau_s \ll \tau_\phi$ , the temperature dependence of the interference correction is metallic-like,<sup>8</sup>  $\delta\sigma^{WL} = 0.5 G_0 \ln(\tau_\phi/\tau)$ , and the magnetoconductivity becomes positive over the whole magnetic field range.

The spin relaxation influences the interaction correction as well.<sup>9</sup> This correction can be conventionally considered as the sum of two parts. The first part originates from the exchange contribution, and the second one from the Hartree contribution. They are usually referred as the correction in the singlet and triplet channels. The singlet exchange conductivity correction is independent of the magnetic field and spin relaxation rate. It favors

the localization and is equal to  $G_0 \ln(T\tau)$  in the diffusion regime,  $T\tau \ll 1$ . The triplet Hartree conductivity correction is antilocalizing and it depends on the  $e$ - $e$  interaction constant. When the  $e$ - $e$  interaction is not very strong,  $k_F r_0 \gtrsim 0.1$ , where  $k_F$  and  $r_0$  are the Fermi quasi-momentum and screening length, respectively, the triplet contribution is comparable in magnitude with the singlet one, although its absolute value is somewhat less, and the total interaction correction is localizing.<sup>10</sup> In contrast to the singlet contribution, the triplet term is sensitive to the external magnetic field and spin relaxation processes. The magnetic field suppresses two of three triplet contributions<sup>11-17</sup> due to the Zeeman effect. As a result the total interaction correction consists of the singlet and one triplet contributions when the magnetic field is rather high,  $g\mu_B B \gg T$ , where  $g$  is the effective Landé  $g$ -factor. The spin relaxation processes suppresses all the three triplet contributions already at  $B = 0$  if  $T\tau_s \ll 1$ .<sup>8,18</sup> In this case the whole interaction correction comprises only the singlet term and should not depend on the magnetic field.

As far as we know, the suppression of the triplet contributions in systems with the growing spin relaxation rate predicted theoretically did not observed experimentally, although it is invoked to interpret the experimental results in different 2D systems.<sup>19,20</sup> This is not surprising, because a reliable extraction of the  $e$ - $e$  interaction contribution to the conductivity is a intricate challenge. To solve it, one needs, as a rule, to investigate special structures with the given disorder strength, conductivity and  $T\tau$  values.<sup>21</sup> A clear indication of the complexity of this problem is the fact that the quantitative determination of the interaction contributions and the elucidation of the role of intervalley transitions is a widely debated topic even in the popular Si based MOS structures.

In this paper we present the results of the experimental studies of the  $e$ - $e$  interaction contribution to the conductivity of the single quantum well heterostructures  $\text{InP}/\text{In}_x\text{Ga}_{1-x}\text{As}/\text{InP}$ ,  $x = 0.53$ . Earlier, the WL and  $e$ - $e$  interaction corrections in analogous structures but with lower indium content,  $x \simeq 0.2$ , are thoroughly studied in a number of papers (see Refs. 22-24 and refer-

ences therein). The spin-orbit interaction in such type of structures is rather weak and the experimental results are consistent with the well known theories.<sup>2,3,9,11–14</sup> The increase of the indium content results in the narrowing of the energy gap, decrease of the electron effective mass, increase of the effective  $g$  factor and, what is more important, to the strengthening spin-orbit interaction. The last effect leads to reduction in the spin relaxation time so that the condition  $1/T\tau_s \gg 1$  can be fulfilled at easily achievable temperatures,  $T \gtrsim 1$  K. The WL effects in  $\text{In}_x\text{Ga}_{1-x}\text{As}$  quantum wells with relatively high indium content,  $x \simeq 0.53$ , is thoroughly investigated in Refs. 25 and 26. The authors show that the theory<sup>27</sup> developed within the framework of the diffusion approximation is unable to describe the data for the high mobility structures. To interpret the data, the authors attract the theory<sup>28,29</sup> working over the whole ranges of the temperature and classically weak magnetic fields. Thus, the  $\text{In}_x\text{Ga}_{1-x}\text{As}$ , quantum wells with  $x \simeq 0.5$  are suitable systems to study the effect of the spin-orbit interaction on the  $e$ - $e$  interaction contribution to the conductivity. Analyzing the temperature and magnetic field dependences of the conductivity components over the temperature range from 0.6 K to 4.2 K for the electron densities  $(1.3-3.0) \times 10^{11} \text{ cm}^{-2}$  we find no suppression of the interaction correction in the triplet channel up to  $1/T\tau_s \simeq 25$  contrary to the theoretical expectations.<sup>8,9,18</sup>

## II. THEORETICAL BACKGROUND

In the absence of the magnetic field, the interaction correction in the diffusion regime,  $T\tau \ll 1$ , is given by<sup>9,11,14,30–32</sup>

$$\frac{\delta\sigma_{xx}^{ee}}{G_0} = K_{ee} \ln T\tau, \quad (1)$$

where

$$K_{ee} = 1 + 3 \left[ 1 - \frac{1 + \gamma_2}{\gamma_2} \ln(1 + \gamma_2) \right] \quad (2)$$

with  $\gamma_2$  standing for the Landau's Fermi liquid amplitude. The two terms in Eq. (2) are the singlet and triplet channels mentioned above. The specific feature of the interaction correction in the diffusion regime is the fact that in the presence of magnetic field it contributes to  $\sigma_{xx}$  and not to  $\sigma_{xy}$ .<sup>9</sup> As already noted, the magnetic field does not change the singlet contribution but suppresses the triplet one so that only one of three triplet parts is alive when the Zeeman splitting  $g\mu_B B$  becomes much larger than the temperature. The magnetic field dependence of  $\delta\sigma_{xx}^{ee}$  is given by

$$\begin{aligned} \frac{\delta\sigma_{xx}^{ee}}{G_0} = & \left[ 1 + 1 - \frac{1 + \gamma_2}{\gamma_2} \ln(1 + \gamma_2) \right] \ln T\tau \\ & + 2 \left[ 1 - \frac{1 + \gamma_2}{\gamma_2} \ln(1 + \gamma_2) \right] \ln F(B, T\tau), \end{aligned} \quad (3)$$

where  $F(B, T\tau)$  is a function describing the suppression of the two triplet channels.<sup>14,30</sup> Since  $F(B, T\tau)$  obtained in these papers is rather complicated, it is more convenient to use in practice the following simple expression<sup>17</sup>

$$F(B, T\tau) = T\tau \sqrt{1 + \left( \frac{g\mu_B B}{T} \right)^2}, \quad (4)$$

which well approximates the results from Refs. 14 and 30. In contrast to the Zeeman effect, the spin-orbit interaction should suppress all the three triplet contributions so that the interaction correction consists of only one singlet channel when  $1/T\tau_s \gg 1$  even in zero magnetic field. To the best of our knowledge, it is unknown until the present how the triplet contribution is functionally suppressed with the growing spin relaxation rate. Intuitively it can be written by analogy with Eqs. (3) and (4) as follows

$$\begin{aligned} \frac{\delta\sigma_{xx}^{ee}}{G_0} = & \ln T\tau + 3 \left[ 1 - \frac{1 + \gamma_2}{\gamma_2} \ln(1 + \gamma_2) \right] \\ & \times \ln T\tau \sqrt{1 + (T\tau_s)^{-2}}. \end{aligned} \quad (5)$$

If one uses the parameters which are typical for the samples investigated ( $\gamma_2 = 0.6$ ,  $\tau_s = 2 \times 10^{-12}$  s and  $\tau = 3 \times 10^{-13}$  s), we obtain that the triplet contribution [the second term in Eq. (5)] to the temperature dependence of  $\delta\sigma_{xx}^{ee}$  becomes negligibly small as compared with the singlet one (the first term) at  $1/T\tau_s \simeq 4$  corresponding to  $T = 1$  K.

## III. EXPERIMENTAL DETAILS

We studied a  $\text{InP}/\text{In}_x\text{Ga}_{1-x}\text{As}/\text{InP}$  quantum well structure grown by chemical beam epitaxy on an  $\text{InP}$  (100) substrate.<sup>33</sup> The structure CBE06-173 consists of a 50-nm Be-doped layer followed by 75-nm undoped  $\text{InP}$  buffer layer, 12.5-nm Si-doped  $\text{InP}$  layer, a 12.5 nm spacer of undoped  $\text{InP}$ , a 10 nm  $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$  quantum well, and 37.5 nm cap layer of undoped  $\text{InP}$ . The samples were etched into standard Hall bars. To change the electron density in the well, an Al gate electrode was deposited by thermal evaporation onto the cap layer through a mask. In some cases the electron density and the conductivity were controlled through the illumination due to the persistent photoconductivity effect. The results for equal electron densities were mostly identical in both cases. Experiments were performed in a  $\text{He}^3$  system with temperatures from 4.2 K down to 0.5 K.

## IV. RESULTS AND DISCUSSION

Because the leading parameter determining the suppression of the interaction correction in the triplet channel is  $T\tau_s$  value, we begin our consideration with the determination of the spin relaxation time in the sample investigated. One of the way to do this is the analysis

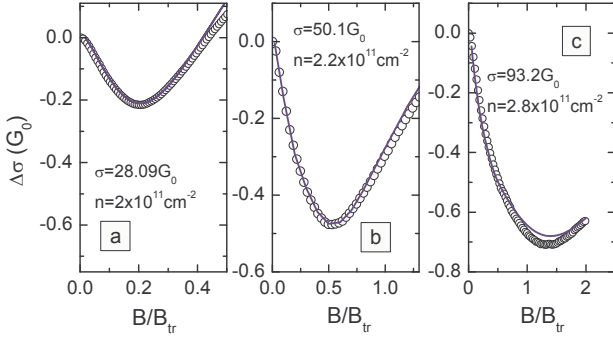


FIG. 1. (Color online) The magnetic field dependences of  $\Delta\sigma$  for the different conductivity controlled by the gate voltage at  $T = 1.35$  K. Symbols are the data, the curves are the results of the best fit by the theory.<sup>28,29</sup>

of the low magnetic field magnetoconductivity  $\Delta\sigma(B) = 1/\rho_{xx}(B) - 1/\rho_{xx}(0)$  caused by the suppression of the interference quantum correction. Figure 1 shows the low-field magnetoconductivity measured at  $T = 1.35$  K as a function of a normalized magnetic field  $B/B_{tr}$  for different conductivity values, where  $B_{tr} = \hbar/2el^2$  with  $l$  as the mean free path is the transport magnetic field. One can see that the negative magnetoconductivity in low magnetic fields followed by the positive magnetoconductivity in higher ones is observed for all the cases. Such the behavior is the clear indication of the fact that the spin relaxation time is shorter than  $\tau_\phi$ . The  $\tau_\phi$  and  $\tau_s$  values are obtained from the fitting of the experimental data by the theoretical expression. It should be emphasized that the reliable determination of these values is possible only in the case when the fit is done in the magnetic fields involving the region in which the antilocalization minimum is observed. The expression obtained in Refs. 6 and 7 for the diffusion regime, when  $\tau/\tau_\phi$ ,  $\tau/\tau_s$ ,  $B/B_{tr} \ll 1$ , is widely used for this purpose. However it is inapplicable for our case, because the antilocalization minimum is observed at relatively high magnetic fields,  $B \sim B_{tr}$ , as seen from Figs. 1(b) and 1(c). As shown in Ref. 26 the phase and spin relaxation times can be reliably obtained in these samples by fitting the experimental data using the model,<sup>28,29</sup> which is developed for arbitrary values of  $\tau$ ,  $\tau_\phi$ ,  $\tau_s$ , and magnetic field. Inspection of Fig. 1 shows that the theory<sup>28,29</sup> describes the experimental results rather well that allows us to extract the spin relaxation and phase breaking times for the different temperatures and the conductivity values.

Note the temperature dependences of  $\tau_\phi$  and  $\tau_s$  (not shown in the figures) are reasonable over the whole conductivity range,  $\sigma \simeq (20 - 100) G_0$ . The spin relaxation time is independent of the temperature within the accuracy of the experiment. Such the behavior is natural for the degenerate electron gas ( $E_F/T > 20$  under our experimental conditions). The temperature dependence of  $\tau_\phi$  is close to  $1/T$  that is typical for the 2D electron gas at low temperatures when the main dephasing mechanism

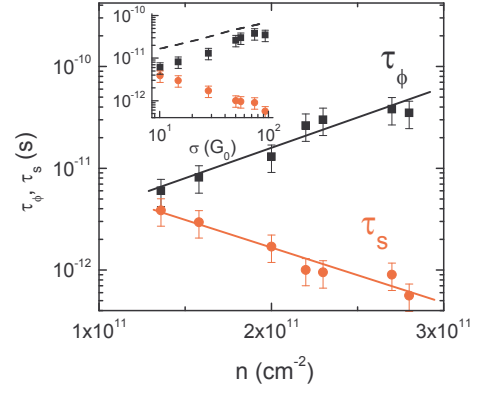


FIG. 2. (Color online) The phase and spin relaxation times at  $T = 1.35$  K as a function of electron density and conductivity (in the inset). Symbols are the data, the solid lines are provided as a guide for the eye. The dashed line is calculated according to Ref. 34.

is the inelasticity of the  $e$ - $e$  interaction.<sup>9</sup>

Figure 2 shows the spin relaxation and phase breaking time plotted against the electron density and conductivity. One can see that  $\tau_s$  is shorter than  $\tau_\phi$  for all the densities. The dephasing time increases with the increasing conductivity that agrees with the theoretical prediction.<sup>34,35</sup> The spin relaxation time decreases with the  $n$  increase. The origin is transparent. As shown in Refs. 25 and 26 the spin relaxation in such the type of samples at low temperatures is controlled by the Dyakonov-Perel mechanism.<sup>36</sup> For this mechanism the spin relaxation time is determined both by the spin orbit splitting at the Fermi energy  $\hbar\Omega$  and the transport relaxation time:  $\tau_s = 1/(2\Omega^2\tau)$ . As shown in Ref. 26 the spin orbit splitting in these samples is caused by the Rashba effect<sup>37</sup> and it linearly depends on the Fermi quasimomentum  $k_F$ :  $\hbar\Omega = \alpha k_F = \alpha\sqrt{2\pi n}$  where  $\alpha$  is the constant depending on the asymmetry of the quantum well. So, since both quantities  $\tau$  and  $\hbar\Omega$  increase when  $n$  increases, the decrease of  $\tau_s$  in Fig. 2 observed experimentally is natural.

Thus we have obtained the phase breaking and spin relaxation times over the whole conductivity range. As seen from Fig. 2 the spin relaxation time decreases from  $\tau_s \approx 4 \times 10^{-12}$  s to  $\tau_s \approx 5 \times 10^{-13}$  s with changing electron density within the range from  $1.4 \times 10^{11}$  cm<sup>-2</sup> to  $2.8 \times 10^{11}$  cm<sup>-2</sup>. It means that parameter  $\hbar/\tau_s = (2 - 15)$  K is greater or much greater than the temperature under our experimental conditions and the sample is good candidate for studying the role of spin effects in the  $e$ - $e$  interaction correction to the conductivity.

Now we are in position to consider the interaction quantum correction to the conductivity. The diffusion contribution  $\delta\sigma_{xx}^{ee}$  can be obtained by eliminating the interference correction and the ballistic part of interaction correction with the use of the method described in Ref. 21. Because both the interference correction and the ballistic part are reduced to the renormaliza-

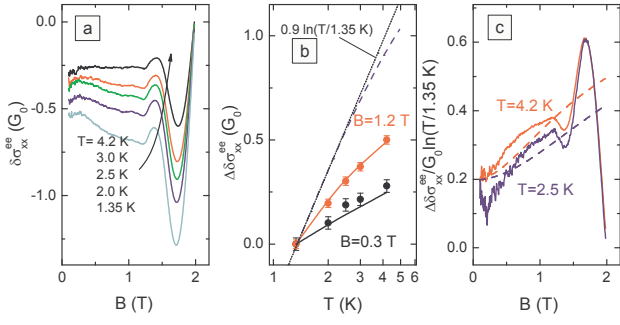


FIG. 3. (Color online) (a) – The experimental magnetic field dependences of  $\delta\sigma_{xx}^{ee}$  for the different temperatures. (b) – The dependences  $\Delta\delta\sigma_{xx}^{ee}(T) = \delta\sigma_{xx}^{ee}(T) - \delta\sigma_{xx}^{ee}(1.35 \text{ K})$  for  $B = 0.3 \text{ T}$  and  $1.2 \text{ T}$ . The symbols are the data, the solid lines are calculated from Eqs. (3) and (4), the dashed line is calculated from Eq. (5). (c) – The magnetic field dependences of  $\Delta\delta\sigma_{xx}^{ee}(T)/\ln(T/1.35 \text{ K})$  for  $T = 4.2 \text{ K}$  and  $2.5 \text{ K}$ . Solid lines are the experimental results. Dashed lines are calculated from Eq. (5). The results presented in all the panels are obtained at  $n = 2 \times 10^{11} \text{ cm}^{-2}$ ,  $\sigma(T = 1.35) = 28.09 G_0$ .

tion of the mobility and, therewith, the diffusion part of the correction does not contribute to the off-diagonal component of the conductivity, one can obtain the mobility  $\mu$  from  $\sigma_{xy}$  knowing the electron density (from the period Shubnikov-de Haas oscillations)  $\mu(B, T) = \sqrt{\sigma_{xy}/(en - \sigma_{xy}B)}B$  and find the correction  $\delta\sigma_{xx}^{ee}$  as the difference between the experimental value of  $\sigma_{xx}$  and the value of  $en\mu/(1 + \mu^2 B^2)$ . As an example we demonstrate the  $B$  dependences of  $\delta\sigma_{xx}^{ee}$  obtained in such a way at different temperatures for  $n = 2 \times 10^{11} \text{ cm}^{-2}$  in Fig. 3(a). Two specific features are evident. The lower temperature the more negative the interaction correction  $\delta\sigma_{xx}^{ee}$ . The  $\delta\sigma_{xx}^{ee}$  value increases in magnitude with the growing magnetic field.

The experimental temperature dependences of  $\Delta\delta\sigma_{xx}^{ee}$  taken at different magnetic fields are shown by symbols in Fig. 3(b). One can see that the dependence  $\Delta\delta\sigma_{xx}^{ee}(T) = \delta\sigma_{xx}^{ee}(T) - \delta\sigma_{xx}^{ee}(1.35 \text{ K})$  is close to the logarithmic one at low magnetic field,  $B = 0.3 \text{ T}$ , and perceptibly deviates from that at stronger field,  $B = 1.2 \text{ T}$ . Furthermore, it becomes steeper with growing magnetic field that is better evident from Fig. 3(c) where the quantity  $\Delta\delta\sigma_{xx}^{ee}(T)/\ln(T/1.35 \text{ K})$  for  $T = 4.2 \text{ K}$  and  $2.5 \text{ K}$  against the magnetic field is depicted.

Such the behavior of  $\delta\sigma_{xx}^{ee}$  with growing temperature and magnetic field is typical for the systems the relatively large value of  $g$ -factor (see, for instance, Ref. 38). In the low magnetic field, the Zeeman splitting is small as compared with the temperature. Really, if one uses  $g = 2$  determined experimentally from the analysis of the angle dependence of the Shubnikov-de Haas oscillations amplitude, we obtain  $g\mu_B B/T \simeq 0.2$  at  $T = 2 \text{ K}$  and  $B = 0.3 \text{ T}$ . In this case  $F(B, T\tau) \simeq T\tau$  as it follows from Eq. (4), i.e., the triplet contribution is not suppressed and the temperature dependence of  $\delta\sigma_{xx}^{ee}$  is logarithmic

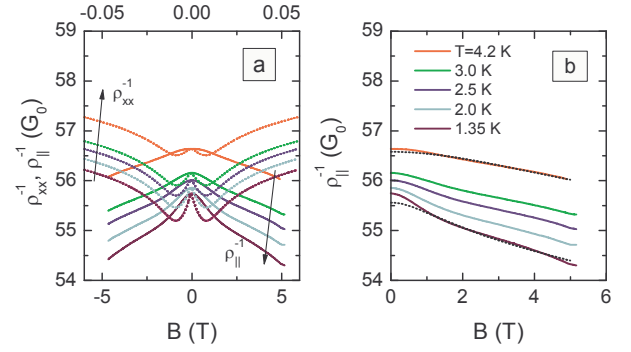


FIG. 4. (Color online) (a) – The experimental magnetic field dependences of the conductivity measured in the transverse (dotted curves) and longitudinal (solid curves) orientations of the magnetic field for the different temperatures. (b) – The longitudinal magnetoconductivity for different temperatures measured experimentally (solid curves) and calculated (dotted curves) according to Ref. 15.

with the slope determined only by the value of interaction constant  $\gamma_2$  according to Eq. (2). Because the Zeeman splitting increases with the growing magnetic field, its role becomes more significant, that results in suppression of the triplet contribution. This effect manifests itself as the increase of absolute value of  $\delta\sigma_{xx}^{ee}$  and the increase of the slope of the  $\Delta\delta\sigma_{xx}^{ee}$  vs  $\ln T$  dependence with increasing magnetic field. As seen from Figs. 3(b) and 3(c) the experimental data are well described in framework of this model. The curves calculated from Eq. (4) with  $\gamma_2 = 0.64$  [that corresponds to  $K_{ee} = 0.2$  in Eq. (2)] and  $g = 2$  run practically over the experimental points.

Thus we do not detect the suppression of the  $e$ - $e$  interaction correction by the spin-orbit interaction at  $B = 0$  when investigating the magnetoresistivity in the transverse magnetic field. The experimental results are well described by the theory taking into account only the Zeeman effect, even though the triplet contribution and, hence, the magnetic field dependence of the whole interaction correction are expected to be strongly suppressed due to the fast spin relaxation.

It would seem that more straightforward way to investigate the  $e$ - $e$  interaction correction is to take the measurements in in-plane magnetic field,<sup>15</sup> where the off-diagonal component of the conductivity tensor is equal to zero. The experimental magnetic field dependences of the conductivity measured in the transverse (dotted curves) and longitudinal (solid curves) orientations of the magnetic field measured at the different temperatures for  $n = 2.2 \times 10^{11} \text{ cm}^{-2}$  are shown in Fig. 4(a). The nonmonotonic behavior of the transverse magnetoconductivity is caused by the suppression of the interference quantum correction in this magnetic field range. As for the longitudinal orientation, one can see that two regions of the magnetic field can be distinguished (note, the scale for the longitudinal orientation is hundred times larger than that for the transverse one). This is region

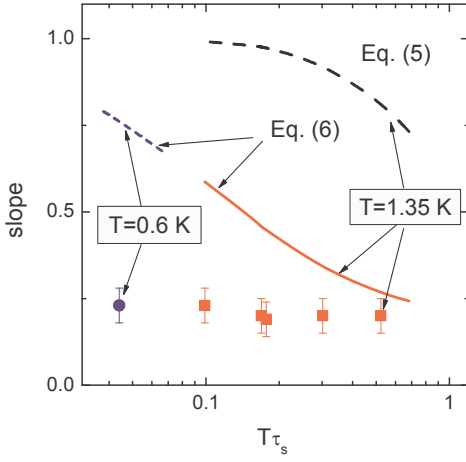


FIG. 5. (Color online) The slope of the temperature dependence of the  $e$ - $e$  interaction correction,  $G_0^{-1}d\sigma/d\ln T\tau$ , as a function of  $T\tau_s$ , calculated from Eq. (5) and Eq. (6) (lines) and obtained experimentally (symbols) for  $T = 0.6$  K and 1.35 K.

of low field,  $B \lesssim 1.5$  T, corresponding to the faster decrease of the conductivity  $\rho_{\parallel}^{-1}$  with growing magnetic field, and the region of the higher magnetic field characterized by the smaller curvature of the magnetoconductivity curves. The behavior of  $\rho_{\parallel}^{-1}$  in the first region, in which the conductivity decreases on the value close to the depth of the antilocalization minimum observed in transverse magnetic field, is dictated by the suppression of the weak antilocalization caused by roughness of the quantum well interfaces.<sup>39–41</sup> The run of the magnetoconductivity curves in higher magnetic field is controlled by the suppression of the triplet contribution to the interaction-induced quantum correction due to the Zeeman effect. The latter is clearly evident from Fig. 4(b), where our data are presented together with the results of the theoretical calculations.<sup>15</sup> The theoretical curves were calculated with  $F_0^\sigma = -0.39$  for the diffusion part of the correction (that corresponds to  $\gamma_2 = -F_0^\sigma/(1 + F_0^\sigma) = 0.64$  found above), and  $F_0^\sigma = -0.07$  for the ballistic part.

It must be noted here that the experiments in in-plane magnetic field cannot independently provide a reliable information about the singlet and triplet contributions to the interaction correction. The reason is that the two different interaction constants are responsible for the ballistic and diffusion contributions to interaction correction,<sup>10</sup> and the data for this orientation can be satisfactorily described by different sets of these constants. Nevertheless, we would like to stress that the results for the in-plane orientation of magnetic field are consistent with that obtained in the transverse orientation: the longitudinal magnetoconductivity is well described by the interaction constant, which value,  $F_0^\sigma = -0.39$ , has been obtained from the analysis of the  $T$  and  $B$  dependences of  $\sigma_{xx}$ .

Thus, the experimental results obtained for both ori-

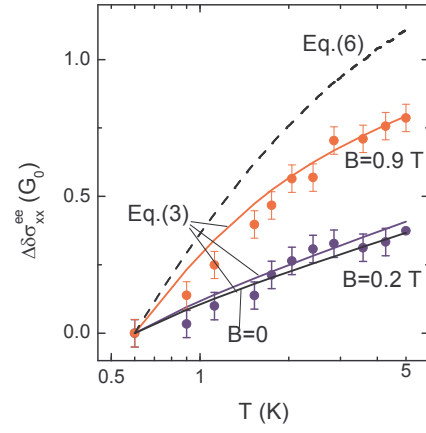


FIG. 6. (Color online) The temperature dependence of  $\Delta\sigma_{xx}^{ee} = \delta\sigma_{xx}^{ee}(T) - \delta\sigma_{xx}^{ee}(0.6 \text{ K})$  for  $n = 2.8 \times 10^{11} \text{ cm}^{-2}$  at different magnetic fields. The symbols are the experimental results. The solid and dashed lines are calculated according to Eq. (3) and Eq. (6), respectively. The following parameters have been used:  $\gamma_2 = 0.653$ ,  $g = 2$ ,  $\tau = 6.5 \times 10^{-13} \text{ s}$ , and  $\tau_s = 6 \times 10^{-13} \text{ s}$ .

entations of the magnetic field are adequately described by taking into account only the Zeeman effect resulting in suppression of the two of three triplet contributions with growing magnetic field.

This observation is in conflict with our expectations propounded in Section II. It is well evident from Fig. 5, where the data for different electron density are collected. Squares in this figure are the experimental values of  $K_{ee}$  at  $B = 0$  plotted against the value of  $T\tau_s$ , where  $\tau_s$  is controlled by the electron density, while  $T$  is kept constant,  $T = 1.35$  K. The dashed line is the slope of the  $T$  dependence of the interaction correction,  $G_0^{-1}d\sigma^{ee}/d\ln(T\tau)$ , calculated from Eq. (5). According to Eq. (5) the triplet channel should be fully suppressed by SOI already at  $T\tau_s \simeq 0.3$  (it corresponds to  $\tau_s = 2 \times 10^{-12} \text{ s}$  for  $T = 1.35$  K); the slope is expected to be equal to approximately 0.9 instead of 0.2 observed experimentally.

A more accurate expression for the interaction correction in the presence of spin-orbit interaction (assuming the simplest case when all the three triplets are suppressed by the same  $\tau_s$ ) can be written<sup>42</sup> similarly to the expression for the Zeeman magnetoresistance:<sup>15,16</sup>

$$\frac{\delta\sigma^{ee}}{G_0} = \ln x - 3 \sum_{n=1}^{1/x} \left[ \frac{y}{ny+1} + \frac{1+\gamma_2}{\gamma_2} \frac{1}{n} \ln \frac{ny+1}{(1+\gamma_2)ny+1} \right], \quad x \ll 1, \quad (6)$$

where  $x = T\tau$  and  $y = 2\pi T\tau_s$ . The suppression of the triplet contribution with growing spin relaxation rate occurs not so fast according to this equation (see solid line in Fig. 5). Nevertheless, the discrepancy between the experimental results and more refined theoretical prediction remains well visible, especially at low  $T\tau_s$  values.

The contradiction between the data and theory becomes all the more evident at lowest temperature,  $T = 0.6$  K, that provides  $T\tau_s \simeq 0.05$  for the highest electron density,  $n = 2.8 \times 10^{11} \text{ cm}^{-2}$ , when  $\tau_s = 6 \times 10^{-13} \text{ s}$ ). The results are shown in Fig. 6. One can see that the temperature dependences of  $\delta\sigma_{xx}^{ee}$  in this figure and in Fig. 3(b) are practically the same despite the fact that the minimal  $T\tau_s$  value in Fig. 6 is six times less than that in Fig. 3(b) (0.05 against 0.3). In this case, too, the experimental data are well described by Eq. (3) which takes into account only the Zeeman effect resulting in suppression of the two triplet channels in growing magnetic field (see Fig. 6). The dashed curve in Fig. 6 is intended to illustrate once again the conflict between our results and theoretical prediction for the role of SOI in the interaction correction. It shows the temperature dependence of  $\delta\sigma_{xx}^{ee}$  for  $B = 0$ , which would be observed if the spin-orbit interaction would suppress the triplet contributions as expected theoretically according to Eq. (6). One can see that the correction calculated increases in magnitude with growing temperature sufficiently steeper than the correction measured at  $B = 0.2$  T so that the experimental slope of the  $T$  dependence of  $\delta\sigma_{xx}^{ee}$  at  $B \rightarrow 0$  is approximately four times less than that found from Eq. (6) [shown in Fig. 5 by the circle and dotted line, respectively].

Thus, the main experimental result of the paper is that the suppression of the triplet contributions to interaction quantum corrections by the spin-orbit interaction at  $B = 0$  does not reveal itself under the experimental conditions when the spin relaxation rate  $1/\tau_s$  is 20–25 times larger than  $k_B T/\hbar$ . All the experimental results are consistently described within the framework of the model, which takes into account the Zeeman effect only.

We would like to complete this work with a short discussion of the possible reason for contradictions between the data and theoretical expectations. Starting point of the theoretical considerations is that the splitting of the energy spectrum due to the spin-orbit interaction is supposed to be much smaller than all the characteristic energies in the system. This approximation works good in the high-mobility systems, in which the fast spin relaxation is accounted for by the large value of the momentum relaxation time. It is not the case for the samples under investigation. The value of the spin-orbit splitting estimated as  $\hbar\Omega = \hbar/\sqrt{2\tau\tau_s}$  is (0.5–0.8) meV for different electron densities, that is 10–15 times larger than the lowest temperature in our experiments,  $T = 0.6$  K. Furthermore, the spin-orbit splitting, being significantly less than  $\hbar/\tau$  for the rightmost point in Fig. 5 for which  $\Omega\tau \simeq 0.15$ , becomes close to  $\hbar/\tau$  for the leftmost point, where  $\Omega\tau \simeq 0.8$  due to simultaneous increase of  $\Omega$  and

$\tau$  with increasing electron density. Thus, the closer the value of  $\Omega\tau$  to unity, the stronger the disagreement between the data and theory. Quite apparently, the spin-orbit splitting of the energy spectrum and multicomponent character of the wave functions should be taken into account from the outset when the interaction-induced correction is estimated theoretically for the systems with strong spin-orbit interaction.

## V. CONCLUSION

We have studied the electron-electron interaction correction to the conductivity of 2D electron gas in the gated single quantum well InP/In<sub>0.53</sub>Ga<sub>0.47</sub>As heterostructures with strong spin-orbit interaction. Analyzing the low magnetic field magnetoconductivity we have obtained the value of the spin relaxation rate for different electron density values, which appears to be relatively high as compared with the temperature. The diffusion part of the interaction correction has been obtained with the use of method based on the unique property of the interaction to contribute to  $\sigma_{xx}$  and do not to  $\sigma_{xy}$ . It has been found that the behavior of the interaction correction with the changing temperature and magnetic field is analogous to that observed in the systems with slow spin relaxation. Although the strong inequality  $1/T\tau_s = 20 - 25 \gg 1$  is fulfilled under our experimental conditions, both the temperature and magnetic field dependences of the interaction correction are quantitatively described in framework of the model developed for  $1/T\tau_s \ll 1$ , in which the Zeeman effect rather than the spin relaxation due to spin-orbit coupling plays the main role.

Thus, despite the fast spin relaxation in the samples under investigation, we do not observe any suppression of the triplet contributions to the interaction quantum corrections to the conductivity of 2D electron gas in the InP/In<sub>x</sub>Ga<sub>1-x</sub>As/InP single quantum wells.

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